Momentum Transfer over the Coastal Zone

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Abstract

Spatial variations of surface stress over the coastal shoaling zone are studied off-shore of Duck, NC, by the research aircraft, LongEZ, equipped to measure both atmospheric turbulence and oceanic waves. We find that the existence of the shoaling zone is clearly defined by the decrease of the mean square slope of the short waves (wavelength shorter than 2m) and the increase of the mean square slope of the long waves (wavelength longer than 2m) with the off-shore distance. However, the spatial variation of the friction velocity with off-shore distance is much larger with off-shore flow than with on-shore flow.

With on-shore flow, the spatial variation of the stress in the coastal zone is small. The friction velocity is strongly correlated with the mean square slope of the oceanic waves. In addition, the variation of the neutral drag coefficient, which represents the variation of the aerodynamic roughness length at a constant observation height, is well correlated with the atmospheric bulk Richardson number. With off-shore flow, the observed momentum flux significantly decreases with off-shore distance. The relationships between the friction velocity and the mean square slope of the short waves, and the relationship between the neutral drag coefficient and the atmospheric bulk Richardson number are obscured by the influence of the upstream land surface within the field of view of the turbulence measurement. However, these relationships agree well with those for the on-shore flow cases, as the off-shore distance increases until the field of view of the momentum transfer is entirely occupied by the ocean. The results in this study suggests that the influence of the strong turbulence from the land surface in off-shore flow may lead to ambiguous physical interpretation of the correlation between the momentum flux and the derived sea state such as the wave age due to self-correlations through the friction velocity.

1. Introduction

Surface stress over the sea has been investigated over open water from ships and aircraft, and coastal water with research towers (Geernaert and Plant, 1990; Weller et al., 1991;

Kraus and Businger, 1994; Mahrt, et al., 1996). Numerous researchers have found that the stress is greater over a young and developing wave field than over an older wave field (Kitaigorodskii, 1973; Geernaert et al., 1987; Donelan, 1990; Donelan et al., 1993). Developing waves are commonly observed with atmospheric flow acceleration (changing wind direction or speed), and fetch limited off-shore flow (Geernaert et al., 1987), while the older wave field is more in equilibrium with the wind field. Young developing waves (small wave age) are dominated by the growth of high-frequency capillary waves riding on long gravity waves and travel slower than the wind, leading to high surface stress (Donelan, 1982; Geernaert et al., 1986). The correlation between the surface wind stress and the sea-surface roughness associated with capillary-gravity waves detected by radar backscattering from altimeters is clearly demonstrated in the literature (Glazman and Pilotz, 1990; Glazman and Greysukh, 1993; Vandemark et al., 1997).

Fully developed waves (large wave age) move with a phase speed close to the wind speed and are associated with relatively low surface stress. Analysis of RASEX (Risoe Air-Sea Experiment) data indicated that most of the variation of the drag coefficient could be explained in terms of wave age although self-correlation through the friction velocity was important and a wind speed correction term explained additional variance (Perrie and Toulany, 1990; Vickers and Mahrt, 1997a). The directional characteristics of the wind, wind stress, and surface waves on the open ocean has been studied by Geernaert (1988a); Geernaert et al. (1993); Rieder et al. (1994); and Friehe et al. (1999).

Interaction between the stress and the sea surface immediately off coast lines are not fully understood (Mahrt et al., 1996; Mahrt et al., 1998; Mahrt, 1999). In the coastal zone, large stress is expected to be associated with shoaling processes and wave breaking as waves propagate into shallow water (Smith, 1980; Freilich and Guza, 1984). As the swell approaches shallow water, it steepens and breaks, and the direction of wave propagation varies with wavelength. Therefore, spatial variations of turbulent fluxes over the coastal zone are expected to be large (Crawford, et al., 1993).

For the first time, the spatial variation of the air-sea interaction in the shoaling zone is studied with both atmospheric and surface-wave observations on board the research aircraft, LongEZ. The momentum flux transfer between the atmosphere and the sea surface is investigated for on-shore and off-shore flows in section 4. The observed atmospheric and oceanic data used in this study is described in section 2. Methods of data analysis are explained in section 3. The summary of the study is in section 5.

2. Observations

Two experiments were conducted off the coast of Duck, North Carolina, one from October 26 to November 12, 1997; and one from March 1 to March 17, 1999. The LongEZ aircraft (Fig. 1) was equipped to measure all three wind components, air temperature, and atmospheric pressure at 50 samples per second, and surface radiation temperature (Everest Interscience Inc., 4000.4GL infrared radiometer) at 1 sample per second (Crescenti et al., 1999). The high sampling rate of the air-motion measurements enables us to calculate atmospheric turbulent fluxes using eddy-correlation methods. The aircraft typically flies at 55 m s^{-1} at 15 m over the sea surface.

Three laser altimeters (Riegl model #LD90-3 VHS) were mounted in an triangle with the triangle legs of 0.93 m, 0.94 m, and 0.94 m to simultaneously measure sea surface wave heights (Vandemark et al., 1999a). The laser range accuracy is better than 2 cm. The minimum surface wave length measured from the laser altimeters is about 2 m. In addition, a downward looking Ka-band radar scatterometer was on board, and its footprint overlays the footprint of the three laser altimeters.

There were 16 aircraft flights conducted in the two-week experiment in November, 1997, and 23 aircraft flights in the three-week experiment in March, 1999. Repeated flights for each flight track were designed to ensure adequate flux sampling. Two major flight patterns were flown: one consists of tracks parallel to the coast line at different off-shore distances; and one consists of many repeated runs along a track perpendicular to the coast line (Fig.2). For the parallel track flight, there were typically two to four passes along each track. For

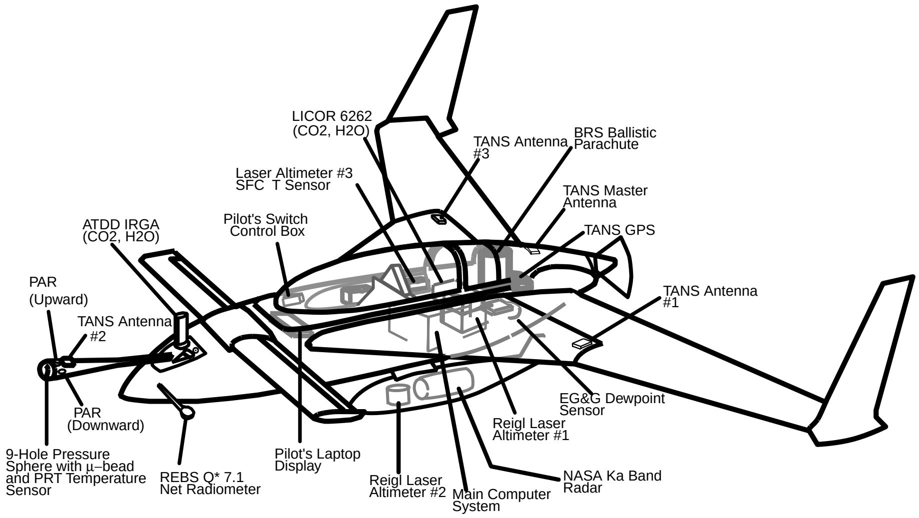

Figure 1: Schematic diagram of the equipment on the NOAA LongEZ.

the perpendicular track flight, there were typically eight passes. During both experiments, the tracks parallel to the coast line are about 20 km long. The track perpendicular to the coast line is about 10 km long, and is extended to 90 km off-shore for some flights. In this study, we focus on four parallel flights (Flights 5, 12, 14, and 15) and two perpendicular flights (Flights 3 and 16) from the 1997 experiment and three parallel flights (Flights 5, 9, and 10) from the 1999 experiment (Table 1). Among these nine flights, the radar data are available for all the flights except Flight 12 from the 1997 experiment. The wind was on-shore for Flights 14 and 15 of the 1997 experiment, off-shore for Flights 3, 5, 12 of the 1997 experiment and Flights 5 and 9 of the 1999 experiment, and almost parallel to the coast line for Flights 16 of the 1997 experiment and Flight 10 of the 1999 experiment (Table 1).

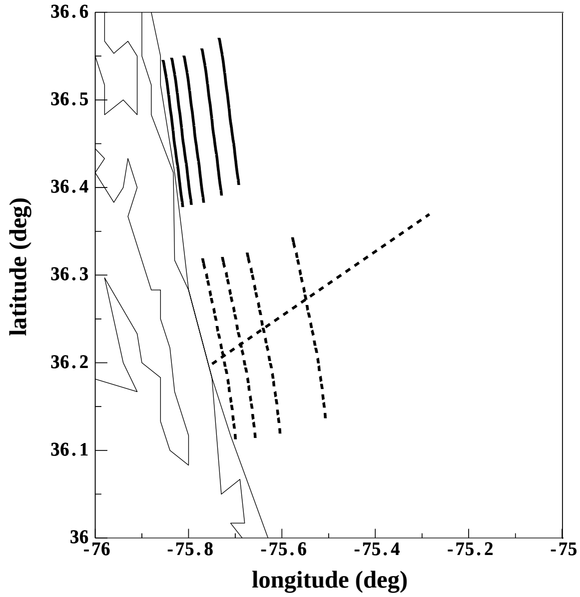

Figure 2: Schematic diagram of flight tracks. The solid lines are the parallel tracks in the 1999 experiment. The dashed lines are the parallel tracks and the perpendicular track in the 1997 experiment.

Table 1 Flight Information

case number	field campaign	flight number	date	time (local)	radar /laser	flow vs. coast	flight track	wind dir.(deg)/ speed (m/s)
1	1997	F3	Nov. 2, 97	1153	yes	off-shore	perpen.	233.8/7.77
2	1997	F5	Nov. 3, 97	1326	yes	off-shore	para.	195.6/7.01
3	1997	F12	Nov. 9, 97	1301	no	off-shore	para.	286.6/8.16
4	1997	F14	Nov. 10, 97	1119	yes	on-shore	para.	32.16/3.56
5	1997	F15	Nov. 10, 97	1347	yes	on-shore	para.	73.8/2.59
6	1997	F16	Nov. 11, 97	0734	yes	parallel	perpen.	356.3/5.76
7	1999	F5	Mar. 4, 99	1052	yes	off-shore	para.	272.4/11.18
8	1999	F9	Mar. 6, 99	1006	yes	off-shore	para.	189.5/7.70
9	1999	F10	Mar. 7, 99	1028	yes	parallel	para.	339.4/13.26

3. Data processing

The aircraft position and velocity are obtained by combining the information from differential GPS (global positioning system) with the information from the accelerometers, where the GPS and the data from the accelerometers are recorded at 10 samples per second and 50 samples per second, respectively. The aircraft platform attitude is obtained by combining TANS (Trmble Advanced Navigation System) GPS attitude, recorded at 10 samples per second, with the information from the accelerometers, recorded at 50 samples per second (Crawford and Dobosy, 1992).

All the aircraft data used for the data analysis in this paper were quality-controlled following Vickers and Mahrt (1997b). After eliminating records with apparent instrumentation problems, the turbulent fluxes are calculated by averaging products of the perturbations from non-overlapping windows of 1 km width. The qualitative results of this study, such as the general character of the spatial variation of turbulent fluxes, were not sensitive to the averaging window size. The flux error for the momentum transfer is less than 8%.

At a 15 m-flight level, the return radar backscatter signal strength from the radar relies on the mean-square-slope of the integrated surface waves for wavelengths from 2.5 cm to 1 m. Since these waves are normally formed on the crests of the longer waves, the radar backscatter signal is actually related to the mean square slope of the integrated surface waves for wavelengths longer than 2.5 cm (Vandemark et al., 1997). The return radar backscatter is quantified as the normalized radar cross section (NRCS), which is inversely correlated with the mean-square slope (mss) of these integrated surface waves (Barrick, 1974; Vandemark et al., 1997),

$$mss = C \cdot 10^{(-NRCS/10)} \tag{1}$$

where C=0.52. The estimated error for NRCS is less than 2 %. The mean square slope of the integrated surface waves represents the sea surface roughness. The dependence of scatterometer returns on very long surface waves is found to be rather weak (Freilich and Challenor, 1994; Lefevre et al. 1994). Theoretical prediction and measurements indicate that surface wind stress and altimeter backscatter are related to partial integration of the wave slope distribution (Brown, 1979; Kitaigorodskii, 1973), particularly in the capillary wave range (Wu, 1972).

The mean square slope of the surface wave for wavelength longer than 2 m can be calculated from the three simultaneous laser altimeter measurements corrected with the aircraft attitude (Vandemark et al., 1999a). The estimated error for the mean square slope of the surface waves from the laser altimeters is less than 5%. Combination of the mean square slope of the integrated surface waves from the radar scatterometer (mss) for the wavelength longer than 2.5 cm and the mean square slope of the surface waves from the laser altimeters (mss_l) for the wavelength longer than 2 m, the mean square slope of the short waves (mss_s) for wavelength shorter than 2 m can be estimated through the following relationship,

$$mss = mss_s + mss_l. \tag{2}$$

All the observed variables, including the turbulent fluxes and the mean-square-slope of the surface waves: mss_s, mss_l, and mss, are averaged from repeated 20 km-long passes over each flight track for the tracks parallel to the coast line to provide one value for each track. The fluxes along the flight tracks perpendicular to the coast line are fitted as a function of off-shore distance based on repeated passes.

The atmospheric stability is expressed in terms of the bulk Richardson number (R_i),

$$R_i = -\frac{g\ \Delta\theta\ z}{\theta_0\ U^2}, \tag{3}$$

where

$$\Delta\theta = T_s - T_a. \tag{4}$$

In Eqs.3 and 4, g is the gravity constant, z is the observation height, θ_0 is the reference potential temperature, set to be 285.15 K, U is the wind speed, and T_s and T_a are the sea skin temperature measured by the infrared radiometer, and the air temperature measured from the LongEZ, respectively.

4. Spatial variations of stress in the shoaling zone

Surface stress ($\vec{\tau}$) between the atmosphere and the sea surface over open water can be estimated as

$$\vec{\tau} = \rho(\overline{w'u'}\ \vec{i} + \overline{w'v'}\ \vec{j}) \tag{5}$$

where ρ is the air density, u', v', and w' are the wind speed components deviated from their corresponding mean in the north-south, $\vec{i}$, the east-west, $\vec{j}$, and in vertical directions, respectively. In this study, the mean value is defined as the non-weighted box average, with the box width of 1km. The strength of the stress can be expressed in terms of the friction velocity (u_*), which is defined as

$$\tau = \rho u_*^2. \tag{6}$$

Based on Monin-Obukhov similarity theory, the friction velocity depends on wind speed, atmospheric stability, and sea surface roughness, i.e.

$$u_* = C_d^{1/2} U, \tag{7}$$

where

$$C_d^{1/2} = \frac{\kappa}{\ln(z/z_0) - \Psi_m(z/L)}. \tag{8}$$

Here C_d is the drag coefficient, U is the mean wind speed, z_0 is the aerodynamic roughness length, κ is the von Karman constant, and Ψ_m is the stability function for momentum expressed in terms of z/L, where L is the Obukhov length. In this study, the Paulson (1970) and Dyer (1974) stability functions are used. The ocean current is assumed to be much smaller than the wind speed in Eq.7. In order to distinguish between the effects of z_0 and z/L on the drag coefficient, the drag coefficient under neutral conditions, defined as

$$C_{d0}^{1/2} = \frac{\kappa}{\ln(z/z_0)}, \tag{9}$$

is used as a surrogate for z_0. That is C_{d0} uniquely increases with z_0 if the observation level z is constant. The aerodynamic roughness length is related to the physical roughness of the underlying surface if the stress is generated by the interaction between the air flow and the underlying surface.

4.1 Spatial variation of stress as a function of off-shore distance

Based on the data set described in section 2, the surface friction velocity significantly decreases with off-shore distance within the first several kilometers off the coast in off-shore flow (Fig.3a), while the spatial variation of the friction velocity is small in on-shore flow (Fig.3b). The difference of the spatial variation of the surface stress between the on-shore

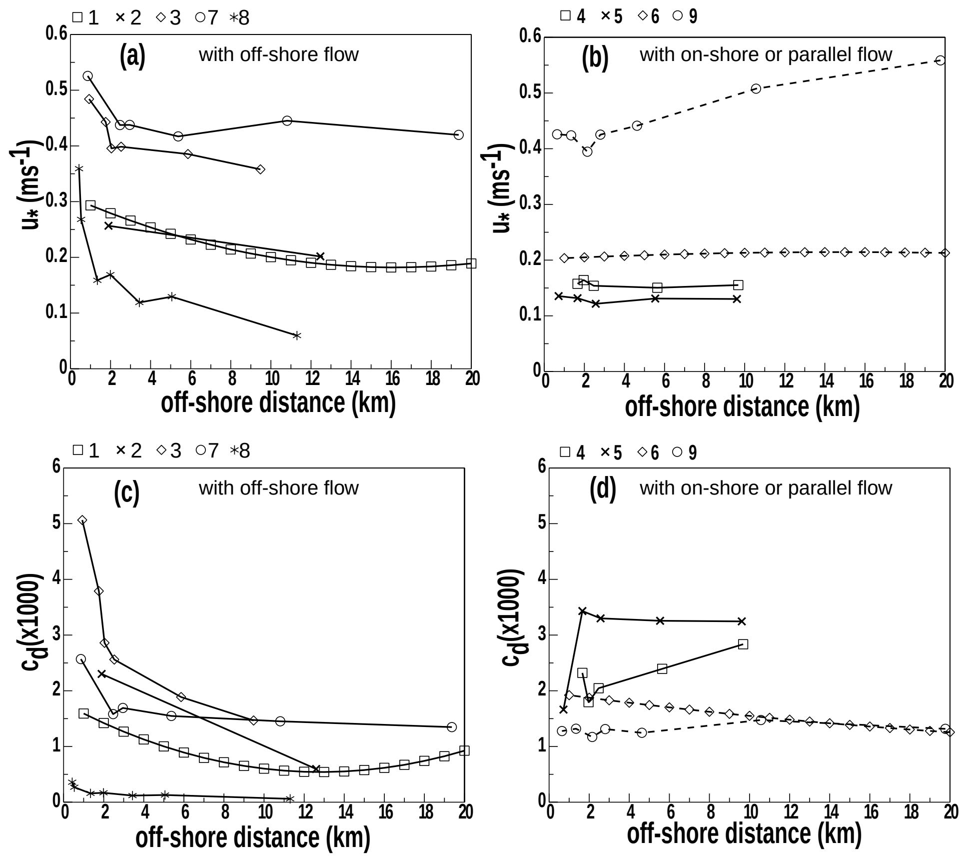

Figure 3: Friction velocity (u_*) (a and b) and drag coefficient (C_d) (c and d) as functions of off-shore distance for on-shore flow (b and d), and off-shore flow (a and c) cases. Each different symbol represents composite results from one flight. The numbers at the top of each panel represent the case number listed in Table 1. The dashed lines in (b) and (d) represent the cases in which the flow is almost parallel to the coast.

and off-shore flow cases is also clearly demonstrated in the drag coefficient (Fig.3c and 3d), in which case the dependence of the stress on the wind speed has been removed (Eq.8). The drag coefficient systematically decreases with off-shore distance in the off-shore flow cases, but not in the on-shore flow cases.

The spatial variation of the friction velocity with off-shore flow is very systematic and cannot be explained by the random flux sampling error. According to Horst and Weil (1994), 90% of the turbulent scalar flux measured at the height of 10 m typically originates from the footprint of 1-2 km upstream although the footprint varies with atmospheric stability and wind speed. Using the footprint theory for scalar quantities as guidance, as the flow travels from the turbulent and rough land surface to the smooth sea surface, the percentage of the land surface within the field of view of the flux measurement decreases. Here the field of view is used in order to distinguish between the momentum transfer and the trace gas transfer. The dramatic decrease of the momentum flux with off-shore distance in Fig.3a and Fig.3d is consistent with the footprint theory. The true interaction between the turbulent air and the sea surface within the field of view of the turbulence measurement is obscured by the strong upstream land influence.

4.2 Relationship between wind stress and sea surface roughness

As momentum is transferred from the atmospheric flow to the ocean by the atmospheric turbulence, surface wind-waves are generated. In general, the mean square slope of the short waves (mss_s) decreases with off-shore distance for both on-shore and off-shore flow cases, and the mean square slope of the long waves (mss_l) increases with off-shore distance (Fig.4). The exception for case 9 in Fig.4d is due to the increase of the wind speed with the off-shore distance (Fig.5). The characteristics of the short and long waves as a function of off-shore distance is consistent with the wave spectra found by Hasselmann et al. (1973).

The increase of mss_l and the decrease of mss_s with off-shore distance implies the existence of the shoaling waves, and increased wavelength with off-shore distance. As the long swell moves towards the coast line, the variation of the bathymetry forces the long waves to shift the energy to shorter waves through shoaling. The sharp decrease of the mean square slope of the long waves due to the shallow water of the coastal zone is particularly clear for case 9 in Fig.4e, in which case the wind was strong.

For the off-shore flow case, the large mean square slope of the short waves close to the coast is also related to the young waves generated by the turbulent air as the sea surface responds to the atmospheric momentum flux quickly. As these waves propagate off-shore, the new wind-generated short waves transfer the energy to longer waves due to wave-wave interaction.

Comparing the spatial variation of mss_s, mss_l, and mss (Fig.4) with the spatial variation of the stress (Fig.3), there is no sharp drop of the mean square slope of either wave category (Fig.4) for the first several kilometers off-shore, in contrast to the sharp decrease of the friction velocity with the off-shore flow. Since the observed momentum flux includes the influence of the upstream land, while the mean square slope of waves represents the sea surface state right under the observational point, the field of view of the two is mismatched. The mismatch of the field of view is not very important if the spatial variation of the surface does not vary dramatically, such as the cases of on-shore flow.

Because the field of view of the momentum flux reduces with decreasing observation height, the difference between the larger momentum flux at higher level due to the land influence and the smaller momentum flux at lower level due to the complete ocean surface leads to vertical momentum flux convergence. The vertical momentum flux convergence accelerates the wind downstream (Fig.5), which is also observed by Smedman et al. (1995).

With on-shore flow, the friction velocity and the mean square slope of either short, long, or the integrated short and long surface waves are closely correlated (Fig.6). This relationship is consistent with previous observations (Brown, et al. 1981, Glazman and Greysukh, 1993; Vandemark et al., 1997; and Vandemark et al., 1999b).

For the off-shore flow case, the friction velocity is not well correlated with the mean square slope of the waves. However, once the data from the first 5 km off the coast are

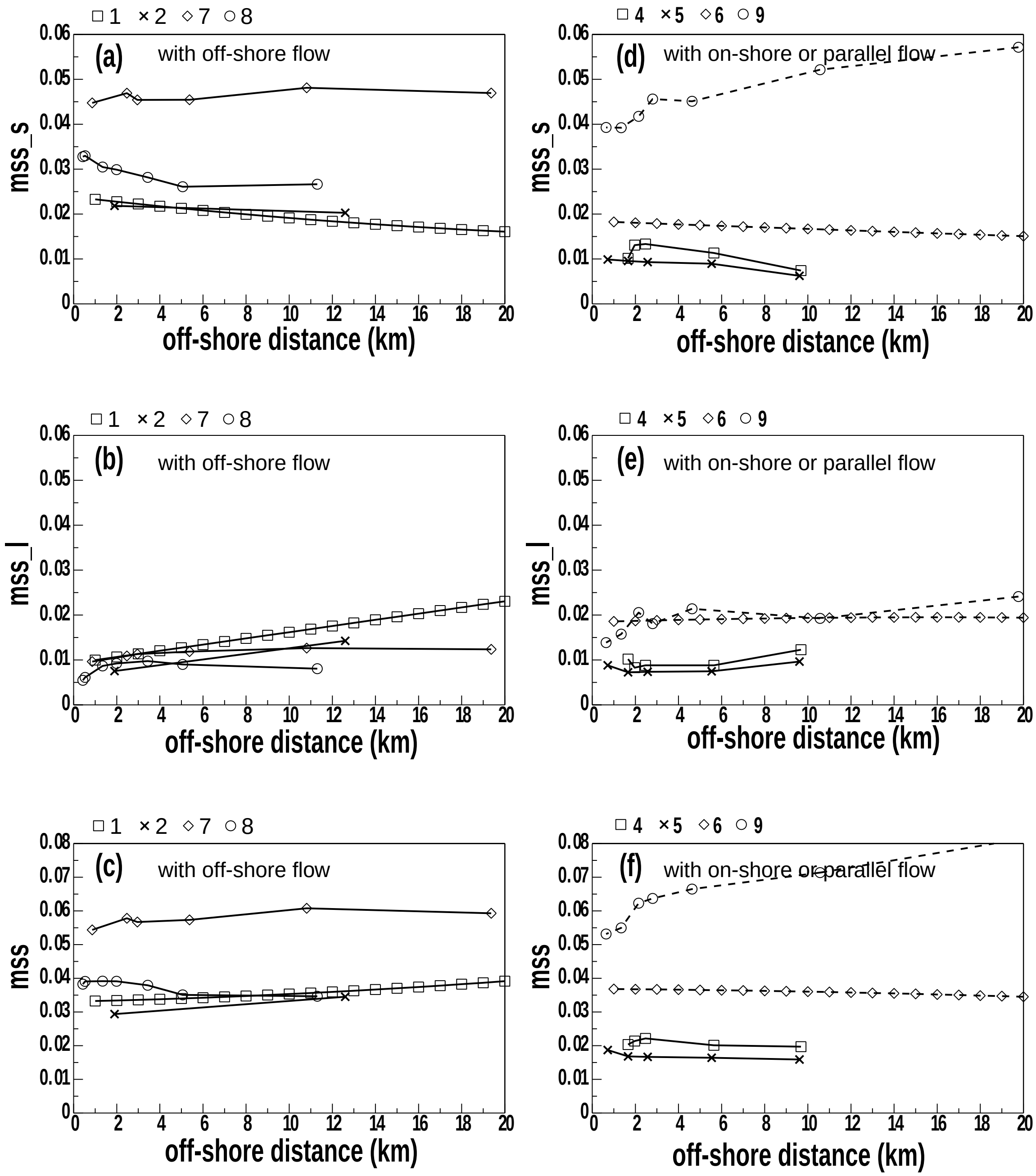

Figure 4: Mean square slopes of short (less than 2 m) (a and d), long (longer than 2 m) surface waves (b and e), and the sum of the short and long surface waves observed by the radar and the laser altimeters (c and f) as functions of the off-shore distance for the on-shore (d, e, and f) and off-shore (a, b, and c) flows. The dashed lines represent the case in which the flow is almost parallel to the coast line.

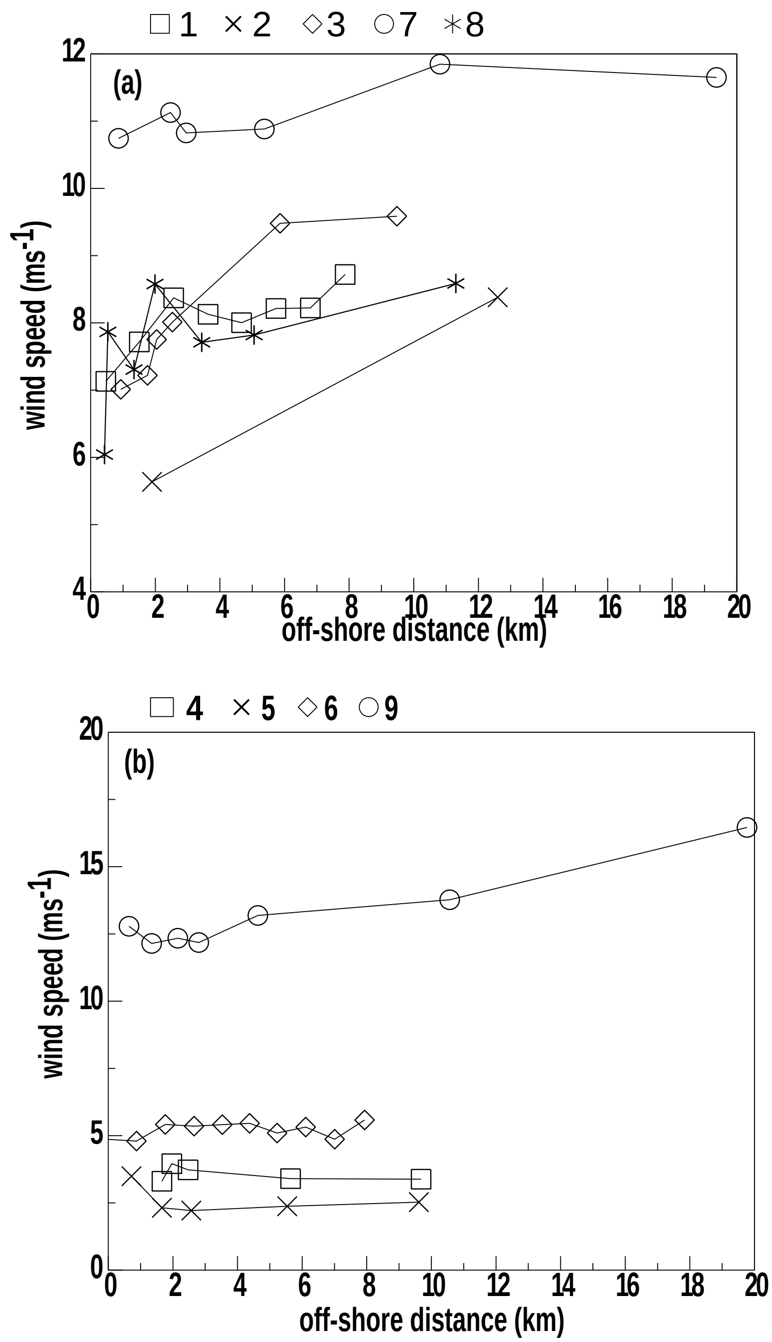

Figure 5: Wind speed as a function of off-shore distance for off-shore flow (a) and on-shore/parallel flow (b).

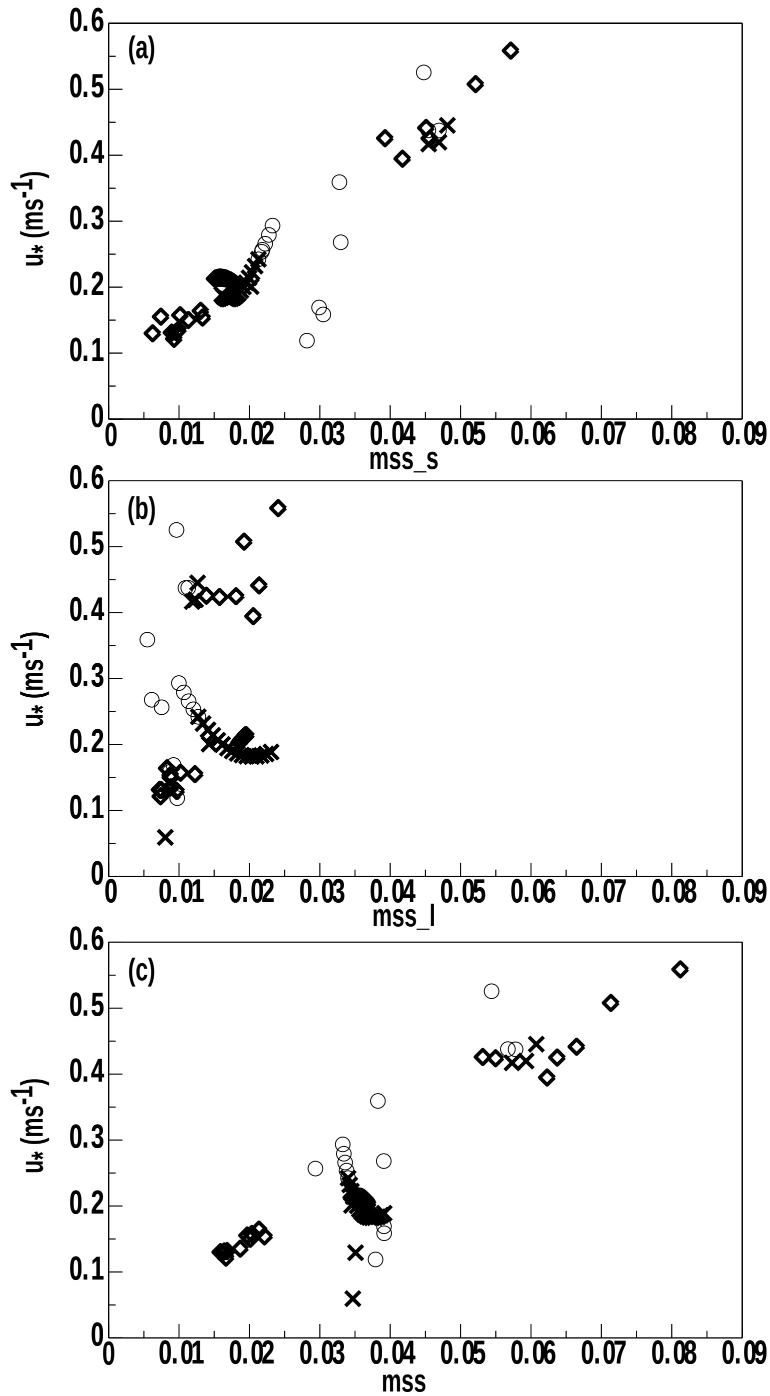

Figure 6: Relationship between the friction velocity and the mean square slope of (a) short surface waves (less than 2 m), (b) long (longer than 2 m) surface waves, and (c) the sum of the short and long surface waves observed by the radar and the laser altimeters for the on-shore (diamonds) and off-shore (circles) flows. The symbol, "x", represents the data for the off-shore flow except the off-distance is larger than 5 km.

excluded, the relationship between the friction velocity and the mean square slope of the short waves agrees reasonably well with the relationship for the on-shore flow.

Hasselmann et al. (1973) found that the evolution of wave spectra for off-shore winds can be described in terms of the shift of the wave peak energy and the variation of the wave spectral width. The energy of the waves increases with off-shore distance and the peak of the wave spectra progressively moves toward lower frequencies as the fetch increases. Vickers and Mahrt (1997a) also find that the wave spectra are broader for the off-shore flow than for the on-shore flow. We would expect that the friction velocity is related to both short (shorter than 2 m) and long (longer than 2 m) surfaces (Rieder and Smith, 1998). Fig.6 shows that the friction velocity is only well correlated with the mean square slope of the short waves, but not long waves if the data within the first 5 km off the coast are excluded. The poor correlation for the long waves may be due to the influence of the non-wind-driven long waves captured by the laser altimeters, such as swell.

4.3 Influence of the atmospheric stability on the wind stress

The surface roughness of the ocean ripples (mainly the capillary waves) is found to increase with the atmospheric instability (Keller et al., 1985; Hwang and Shemdin, 1988; and Wu, 1991). As the atmospheric boundary layer is more turbulent under unstable conditions, sea surface ripples respond more strongly to the pulsating turbulent air movement, and the sea surface roughness is enhanced, in contrast to stability-independent roughness lengths over land surfaces (Sun, 1999).

Figure 7 shows that the aerodynamic roughness length, represented by C_{d0}, does increase with atmospheric instability systematically for the on-shore case where the downward momentum transfer is completely associated with the interaction between the air and the oceanic waves. Since the aerodynamic roughness length is derived from the observed momentum flux based on M-O similarity theory, the computed aerodynamic roughness length close to the coast line is inevitably affected by the upstream land surface as the land surface is within the field of view of the momentum flux measurement. However, the bulk

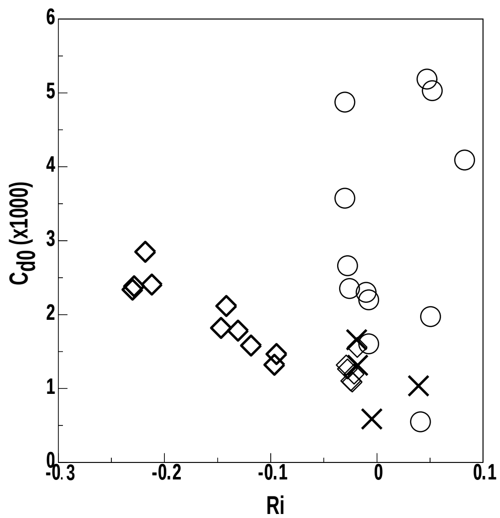

Figure 7: Neutral drag coefficient (C_{d0}) as a function of the bulk Richardson number (R_i) for both on-shore (diamonds) and off-shore flows (circles). The symbol, "x", represent the situation where the wind is off-shore, but the off-shore distance is larger than 5 km.

Richardson number is the bulk parameter based on the mean variables over the sea surface. Therefore, the aerodynamic roughness length is not well correlated with the bulk Richardson number. As the field of view of the momentum flux is occupied completely by the sea surface when the off-shore distance is larger than 5 km, the correlation between the aerodynamic roughness length and the bulk Richardson number agree reasonably well with the correlation for the on-shore flow cases (Fig.7).

The relationship between the aerodynamic roughness length and the atmospheric instability for the on-shore flow cases implies the variation of the atmospheric stability may also play an important role in the spatial variation of the sea surface roughness even when the sea surface roughness is also enhanced by shoaling.

4.4 Discussion

Geernaert (1988b) summarized seven regression formulas for the neutral drag coefficient as a function of wind speed. He found that the neutral drag coefficient was much larger over shallow water than over open water. The large neutral drag coefficient over shallow water cannot all be explained by the fetch dependent sea state. Therefore, the shoaling effect was suggested. As indicated in this study, the large momentum flux observed in the coastal area with off-shore flow is very likely influenced by the advection of the large momentum flux from the land surface, as the land surface occupies a substantial percentage of the footprint of the aircraft flux measurement. Therefore, the advection from the land surface may explain the discrepancy between the observed and modelled, wave dependent neutral drag coefficient in Geernaert (1988b).

Traditionally, the drag coefficient in the coastal zone is studied in terms of fetch and wave age. The wave age is designed to characterize the movement of the wind relative to surface wave motion, and in one version is defined as the ratio of the phase speed of the significant wave relative to the wind speed. When the wave phase speed is much slower than the wind speed (small wave age), strong flow relative to the waves induces large drag at the sea surface. When the wave phase speed is comparable to the wind speed, the surface stress between the atmospheric motion and the moving surface waves is small (Al-Zanaidi and Hui, 1984). However, the interaction between the wind and the surface waves other than the significant wave may also contribute to the surface stress when the wind-wave spectra have a wide band structure, especially when the wind generates waves on the top of the existing long waves (Donelan et al., 1993; Vickers and Mahrt, 1999).

Alternatively, the wave age is computed as the ratio between the phase speed of the significant wave and the friction velocity (Geernaert et al., 1987; Donelan et al., 1993) with the implied assumptions that the field of view of the turbulent fluxes is completely over the sea surface. As demonstrated in this study, the stress over the coastal water can be influenced by the strong turbulence advected from land, which is within the field of view of the momentum flux measurement. The large momentum flux with the off-shore flow would lead to a small value of the wave age (defined with the friction velocity instead of wind speed). The wave age calculated using the observed friction velocity close to the coast would not represent the true wave state until the field of view of the downward momentum transfer is completely occupied by the sea surface. In addition, the frequency bandwidth of wind-waves can be wide so that the phase speed of the peak frequency can be hard to define. Therefore, previous studies on the relationship between the wave age (related to the friction velocity) and the drag coefficient in the coastal zone could be more influenced by self-correlation through the friction velocity, especially for the off-shore cases, rather than representing a true physical relationship between the drag coefficient and the sea state as the wave age is designed for (Anctil and Donelan, 1996).

General fetch-dependent studies of the momentum transfer in the literature may have unknowingly captured the spatial variation of the field of view of the observed flux over the land surface. Using the footprint theory as guidance, the measured flux downstream from the land surface not only depends on the distance between the upstream turbulence source and the measurement point, but also the spatial distribution of the upstream turbulence and the spatial variation of the atmospheric stability. All these factors may cause large scatter in the relationship between fetch and the drag coefficient.

5. Summary

The spatial variation of the interaction between the atmosphere and the sea surface in the coastal zone is studied by the simultaneous measurements of the atmospheric turbulence and the sea surface from the Long-EZ research aircraft. In the shoaling zone, there are distinct differences in the spatial variation of the surface stress and the correlation between the surface stress and the sea surface roughness between the on-shore and off-shore flow cases.

For the on-shore-flow cases, the friction velocity is well correlated with the mean square slope of the short surface waves for the wavelength shorter than 2 m, and the long surface waves for the wavelength larger than 2 m. The mean square slope of the short and long surface waves is derived from the simultaneous measurements from the downward looking Ka-band radar scatterometer and the three laser altimeters on board of the aircraft. The neutral drag coefficient, which represents the aerodynamic roughness length with the constant observation height, is well correlated with the atmospheric bulk Richardson number. These results indicate that there is interaction between the sea surface waves and the turbulent air fluctuations.

However, for the off-shore-flow cases, the stress decreases rapidly with off-shore distance within the first several kilometer off the coast. The sharp decrease of the momentum flux is strongly related to the decrease of the percentage of the upstream land surface with the off-shore distance within the field of view of the turbulent flux measurement, although the interaction between the coastal sea surface and the turbulent air advected from the land surface also contributes to the spatial variation of the momentum flux.

As a result of the influence of the upstream land surface within the field of view of the atmospheric turbulence measurement, the variation of the neutral drag coefficient, or the aerodynamic roughness length in this study, is not correlated with the atmospheric bulk Richardson number within the first 5 km off the coast. When the field of view of the atmospheric turbulence measurement is entirely over the ocean, e.g. for the off-shore distance larger than 5 km, the correlation between the aerodynamic roughness length and the atmospheric bulk Richardson number agrees with the correlation for the on-shore flow cases, and the correlation between the friction velocity and the mean square slope of the short waves is consistent with that for the on-shore flow cases. The influence of the land surface on the coastal momentum flux measurement depends on wind direction and atmospheric stability within the field of view of the turbulence measurement.

Since the wave spectra are broader with the off-shore flow, the wind-driven waves are not limited to the wave range between 2.5 cm and 2 m. However, non-wind-driven waves, such as long swell, can also contribute to the mean square slope of the long waves in our measurement. Therefore, the friction velocity is not well correlated with the mean square slope of the long waves for the off-shore flow cases.

With both on-shore and off-shore flow, in general, the mean square slope of the short waves (shorter than 2 m) decreases with off-shore distance and the mean square slope of the long (longer than 2 m) waves increases with off-shore distance. The spatial variation of the mean square slopes of the short and long waves indicates the existence of the shoaling waves due to the spatial variation of the bathymetry as well as the energy transfer from the short waves to long waves with off-shore distance. The interaction between the turbulent air and the sea surface for the first several kilometers can also contribute to the decrease of the mean square slope of the short waves and the increase of the mean square slope of the long waves. However, without knowing the momentum flux from the sea surface, the relationship between the friction velocity and the sea surface roughness is unknown. Assuming the relationship between the friction velocity and the mean square slope of the short waves for the on-shore flow cases represent the true interaction between the air and the sea surface, the momentum transfer between the air and the sea surface would decrease with off-shore distance, but not as much as the observed one in the coastal zone.

The dependence of the aerodynamic roughness length on the bulk Richardson number indicates that the effect of the shoaling waves on the enhancement of the momentum transfer can be complicated by the effect of the atmospheric stability on the turbulent transfer and the influence of the momentum flux from the upstream land surface.

This study demonstrates the complexity of the air-sea interaction in the coastal shoaling zone, and the importance of the simultaneous observations of the atmospheric conditions and sea state. With the influence of the turbulence from the land surface, the measured momentum flux does not completely reflect the air-sea interaction. The wave age calculated using the observed momentum flux may not represent the true wave state. The interaction between the momentum flux and the variation of the surface waves for the off-shore case needs to be further studied with detailed wave spectra.

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